# PROPOSAL OF POLARIZED $^3$He$^{++}$ ION SOURCE FOR JINR ACCELERATOR COMPLEX

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**Abstract**

It is proposed to develop a source of polarized $^3$He$^{++}$ ions for the JINR Accelerator Complex on the basis of its polarized deuteron source by feeding its radio-frequency dissociator with $^3$He gas to produce metastable atoms, using an existing sextupole magnet and adding a low-field rf transition units.

The radio-frequency transitions of the atomic states of helium-3 in the metastable state are studied. The Schroedinger equations in the uncoupled basis $|\psi_e, \psi_h >$ and also in the basis of stationary states are received. Results of computer simulations agree with published data. The possibility to use two types of the weak field transitions in the helium-3 with different frequencies to get positive or negative values of the helion polarization is shown.

Ionization and accumulation of the polarized helions may be carried out by the electron beam ion source (EBIS) in the reflex mode of operation. The project ionizer parameters are the following: electron energy 10 keV, effective current 5 A, ion trap length 1 m, $^3$He$^{++}$ ion beam intensity $\approx 2 \times 10^{11}$ ions per fast extraction pulse of 8 $\mu$s.

# 1 Introduction

The goal is to make a source of polarized $^3$He$^{++}$ ions (helions) on a basis of the polarized deuteron source for NUCLOTRON-M. The rf dissociator is fed with helium-3 gas for production of $^3$He atoms in the metastable $2^3$S$_1$ state. Stern–Gerlach separation with a sextupole magnet and rf transitions in a weak magnetic field are used for nuclear polarization of the metastable atoms. Ionization to $^3$He$^{++}$ and accumulation of the polarized helions will be carried out by the electron beam ion source (EBIS) in the reflex mode of operation [1].

We note that magnetic moments of a helion and neutron are close in the value: $\mu_h = -2.127\mu_N$ and $\mu_n = -1.913\mu_N$, where $\mu_N$ is the nuclear magneton.

Earlier, the Laval University group (Canada) [2] polarized $^3$He atoms in the metastable state $2^3$S$_1$ (a lifetime of 7860 s) with the electron angular momentum $J = 1$ and then ionized them to $^3$He$^+$ in an electron impact ionizer.

The cold cathode discharge source of metastable atoms produced a flux of $6 \times 10^{15}$ atoms/s sterad with an average velocity of $2.5 \times 10^5$ cm/s. The ionization potential of metastable atoms is quite low, 4.6 eV, compared to 24.6 eV for atoms in the ground state. The ionizer operated in a mode that discriminated between metastable and ground-state atoms, thus producing $^3$He$^+$ from the nuclear polarized metastable atoms.

The subsequent ionization to ³He⁺⁺ was effected by stripping in the base of the Van de Graaf accelerator at 7.5 MV.

The angular momentum of a ³He($2^3S_1$) atom is the vector sum $\vec{F} = \vec{J} + \vec{I}$, where $\vec{J}$ and $\vec{I}$ correspond to the electronic ($J = 1$) and nuclear ($I = 1/2$) angular momenta, respectively.

The spin-dependent part of the Hamiltonian for ³He atoms in the metastable state $2^3S_1$ is

$$\hat{H} = -\mu_J \vec{J}\vec{B}(t) - \mu_h \vec{\sigma}_h \vec{B}(t) - \frac{1}{3}\Delta W \vec{\sigma}_h \vec{J}, \tag{1}$$

where $\vec{\sigma}_h$ is the Pauli spin matrices of the helion, $\vec{J}$ is the electron spin matrices ($J = 1$), $\vec{B}(t)$ is the magnetic field strength, $\Delta W$ is the hyperfine splitting of the ³He atom in the state $2^3S_1$;

$\Delta W = 4.4645 \times 10^{-24}$ J$= \hbar \times 4.2335 \times 10^{10}$ rad/s,
$\mu_J = 2\mu_e = -1.85695275 \times 10^{-23}$ J/T$= -\hbar \times 1.76085977 \times 10^{11}$ rad/s T,
$\mu_h = -1.07455 \times 10^{-26}$ J/T$= -\hbar \times 1.0189 \times 10^{8}$ rad/s T.

Consider at first the case of static magnetic field $B$ directed along the z-axis. The six hyperfine structure stationary states and corresponding eigenvalues are obtained by diagonalizing the $6 \times 6$ static Hamiltonian matrix in the uncoupled $|m_h, m_J>$ basis. The wave functions of the hyperfine states at magnetic fields $B$ and $B \to \infty$ are

$$\Psi_1 = \Psi(1/2, +1/2) = -\sin\beta\,\psi_h^+\psi_J^0 + \cos\beta\,\psi_h^-\psi_J^+ \Rightarrow \psi_h^-\psi_J^+,$$

$$\Psi_2 = \Psi(3/2, +3/2) = \psi_h^+\psi_J^+,$$

$$\Psi_3 = \Psi(1/2, -1/2) = -\sin\alpha\,\psi_h^+\psi_J^- + \cos\alpha\,\psi_h^-\psi_J^0 \Rightarrow \psi_h^-\psi_J^0, \tag{2}$$

$$\Psi_4 = \Psi(3/2, +1/2) = \cos\beta\,\psi_h^+\psi_J^0 + \sin\beta\,\psi_h^-\psi_J^+ \Rightarrow \psi_h^+\psi_J^0,$$

$$\Psi_5 = \Psi(3/2, -1/2) = \cos\alpha\,\psi_h^+\psi_J^- + \sin\alpha\,\psi_h^-\psi_J^0 \Rightarrow \psi_h^+\psi_J^-,$$

$$\Psi_6 = \Psi(3/2, -3/2) = \psi_h^-\psi_J^-,$$

where $\sin\beta = \sqrt{A_+}$, $\cos\beta = \sqrt{1 - A_+}$; $\sin\alpha = \sqrt{A_-}$, $\cos\alpha = \sqrt{1 - A_-}$;

$$A_+ = \frac{1}{2}\left(1 - \frac{x + 1/3}{\sqrt{1 + \frac{2}{3}x + x^2}}\right), \ A_- = \frac{1}{2}\left(1 - \frac{x - 1/3}{\sqrt{1 - \frac{2}{3}x + x^2}}\right);$$

$$x = \frac{B}{B_c}, \ B_c = \frac{\Delta W}{-\mu_J/J + \mu_I/I} = \frac{\Delta W}{-\mu_J + 2\mu_h} = 0.2407\,\text{T}.$$

The Breit–Rabi diagram of six Zeeman hyperfine components of this metastable state is shown in Fig. 1, where the numbers correspond to those of the wave functions $\Psi_1 - \Psi_6$.

The energies of the states $\Psi_1 - \Psi_6$ are

$$W_1 = \frac{\Delta W}{6} - \mu_J\frac{B}{2} + \frac{\Delta W}{2}\sqrt{1 + \frac{2}{3}x + x^2},$$

$$W_2 = -\frac{\Delta W}{3} - \mu_J B - \mu_I B,$$

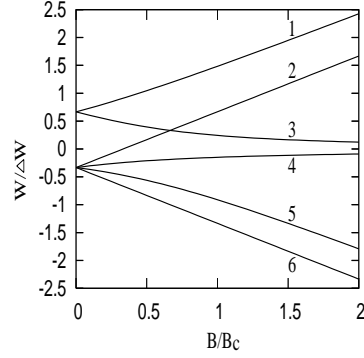$$W_3 = \frac{\Delta W}{6} + \mu_J\frac{B}{2} + \frac{\Delta W}{2}\sqrt{1 - \frac{2}{3}x + x^2},$$

Figure 1: Scheme of the $^3$He($2^3$S$_1$) states showing the hyperfine structure and Zeeman splitting

$$W_4 = \frac{\Delta W}{6} - \mu_J \frac{B}{2} - \frac{\Delta W}{2}\sqrt{1 + \frac{2}{3}x + x^2},$$

$$W_5 = \frac{\Delta W}{6} + \mu_J \frac{B}{2} - \frac{\Delta W}{2}\sqrt{1 - \frac{2}{3}x + x^2},$$

$$W_6 = -\frac{\Delta W}{3} + \mu_J B + \mu_I B,$$

where

$$x = \frac{B}{B_c}, \quad B_c = \frac{\Delta W}{-\mu_J + 2\mu_I} = 0.2407 \text{ T}.$$

Earlier, the SATURNE group [3] reported the results of tests conducted with the use of the known HYPERION polarized ion source fed with $^3$He gas. The dissociator was made of a Pyrex tube with a 2.2 mm diameter nozzle cooled to 80–100 K. The gas flowed for only 3 ms each cycle. The peak rf power was 6 kW at 19 MHz. The ionizer with a reflex electron beam yielded mostly $^3$He$^+$ ions with a pulsed beam current of 50 $\mu$A and pulse duration 1 ms.

The difference between the sextupole magnet "on" and "off" modes was 10 $\mu$A. This value was used to estimate the helion intensity in the proposed helion ion source.

## 2 Design parameters

The atomic beam source under development for the polarized deuteron source for the NUCLOTRON-M has the following characteristics: Dissociator is fed with pulsed rf power, peak 2 kW at 35 MHz, pulse duration 1 ms at 4 Hz. The gas flow through the nozzle 2.2 mm in diameter is $7.4 \times 10^{17}$ molecules/pulse.

Stern–Gerlach separation is effected with a permanent magnet sextupole triplet and an electromagnetic sextupole. Pole tip magnetic fields are from 1.66 to 1.1 T. The sextupoles focus the atomic beam into the ionizer positioned at a distance of 120 cm from the nozzle.

At Figs. 2, 3 the results of computer simulation are shown for two values of the atom velocity 2500 and 1200 m/s. One may see that the $^3$He atomic beam cannot be focused in the given configuration at the velocity $v = 2.5 \times 10^3$ m/s. The cooling of the atomic beam is necessary.
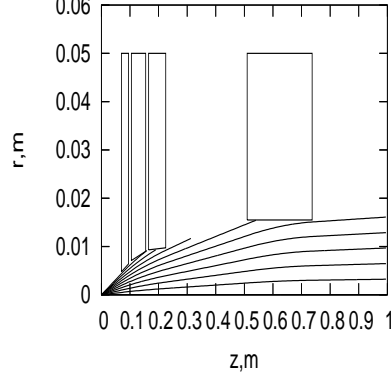
Figure 2:  Trajectories of the atoms in the state $F = 3/2$, $m_F = +3/2$, $v = 2500$ m/s
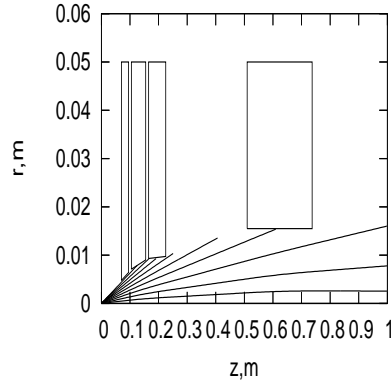


Figure 3:  Trajectories of the atoms in the state $F = 3/2$, $m_F = +3/2$, $v = 1200$ m/s

# 3   Radio-frequency transitions

For hydrogen the task the rf transitions of atomic spin states was considered by E.P. Antishev and A.S. Belov [4]. S. Oh [5] published detailed results for weak field transitions in deuterium. Here we solve this problem for weak field transitions (WFT) in $^3$He in the metastable state $2^3S_1$.

In the uncoupled $|m_h, m_J >$ state basis

$$\Psi(t) = C_1(t)\psi_h^+\psi_J^+ + C_2(t)\psi_h^+\psi_J^0 + C_3(t)\psi_h^+\psi_J^-$$

$$+C_4(t)\psi_h^-\psi_J^+ + C_5(t)\psi_h^-\psi_J^0 + C_6(t)\psi_h^-\psi_J^-$$

and we obtain the following equations for the amplitudes:

$$\frac{dC_1}{dt} = -i/\hbar\{C_1[-(\mu_h + \mu_J)B_z + \Delta W/3] - C_2\mu_J B_x/\sqrt{2} - C_4\mu_h B_x\}$$

$$\frac{dC_2}{dt} = -i/\hbar\{-C_1\mu_J B_x/\sqrt{2} - C_2\mu_h B_z - C_3\mu_J B_x/\sqrt{2} + C_4\sqrt{2}\Delta W/3 - C_5\mu_h B_x\}$$

$$\frac{dC_3}{dt} = -i/\hbar\{\frac{-C_2\mu_J B_x}{\sqrt{2}} + C_3[(-\mu_h + \mu_J)B_z - \Delta W/3] + C_5\sqrt{2}\Delta W/3 - C_6\mu_h B_x\}$$

$$\frac{dC_4}{dt} = -i/\hbar\{-C_1\mu_h B_x + \frac{C_2\sqrt{2}\Delta W}{3} + C_4[(\mu_h - \mu_J)B_z - \Delta W/3] - C_5\mu_J B_x/\sqrt{2}\}$$

4

$$\frac{dC_5}{dt} = -i/\hbar\{-C_2\mu_h B_x + C_3\sqrt{2}\Delta W/3 - C_4\mu_J B_x/\sqrt{2} + C_5\mu_h B_z - C_6\mu_J B_x/\sqrt{2}\}$$

$$\frac{dC_6}{dt} = -i/\hbar\{-C_3\mu_h B_x - C_5\mu_J B_x/\sqrt{2} + C_6[(\mu_h + \mu_J)B_z + \Delta W/3]\}$$

For the polarized $^3$He atomic beam, we need two weak field transition units that should be placed between and after the sextupole magnets. We note that at weak magnetic fields ($x \ll 1$), the level distance $W_1 - W_3 \approx -\frac{4}{3}\mu_J B$, but $W_2 - W_4 = W_4 - W_5 = W_5 - W_6 \approx -\frac{2}{3}\mu_J B$.

It is different from the case of deuterium where all the distances between the levels at $F = 3/2$ and $F = 1/2$ at weak magnetic fields are identical and equal $\approx -2/3\mu_e B$. This fact gives the possibility to use two types of WFT with different frequencies to get positive or negative values of the helion polarization.

If we realize the transition $1 \to 3$ in the free space between the sextupoles, we have after the second sextupole the pure state 2 with $F = 3/2$, $m_F = 3/2$, which gives after ionization $P \approx +1$.

If we realize the transition $1 \to 3$ between the sextupoles and the transition $2 \to 6$ after the second sextupole, we produce the pure state 6 with $F = 3/2$, $m_F = -3/2$, which gives after ionization $P \approx -1$.

For WFT including 1–3 states, $\Psi_1 \longrightarrow \Psi_3$, and 2–6 states $\Psi_2 \longrightarrow \Psi_6$:

$$B_z(t) = B_0 + \frac{dB_z}{dx}vt, \ B_x = B_1(t)\sin\omega t. \tag{3}$$

A tapered electromagnet produces a static magnetic field $B_z(x)$ perpendicular to the beam path with a field gradient $dB_z/dx$ along the magnet ($x = vt$). Atoms pass through a resonant radio-frequency (RF) field in the magnetic field which is a slowly changing function of time because the atoms move through a magnetic field gradient.

We accepted some parameters the same as in the paper by S.Oh: $B_0 = 1.17 \times 10^{-3}$ T, $dB_z/dx = -1.4 \times 10^{-2}$ T/m for a negative static field gradient (or $B_0 = 4.7 \times 10^{-4}$ T, $dB_z/dx = 1.4 \times 10^{-2}$ T/m for a positive gradient),

$l = 5 \times 10^{-2}$ m, $vt_{final} = 5 \times 10^{-2}$ m,

$\omega = 9.63 \times 10^7$ rad/s for $2 \to 6$ transition and $\omega = 1.93 \times 10^8$ rad/s for $1 \to 3$ transition.

It was accepted $v = 1.2 \times 10^3$ m/sec. The rf amplitude $B_1$ is of square dependence of $x = vt$ with a zero value at $x = 0$ and $x = l$. $B_1^{max}$ was some units of $10^{-4}$ T.

Some results of computer calculations in the basis of uncoupled states for an atom velocity 1200 m/s are presented in the Figs. 4, 5.

An evident way for producing polarized helions is to follow the way of the Laval University group and inject the nuclear polarized $^3$He$^+$ ions into the electron beam ion source for subsequent ionization to helions.

But for a pulsed regime there is a possibility of ionizing metastable atoms directly to $^3$He$^{++}$ and accumulating them in the ion trap of the EBIS with subsequent 8-$\mu$s-pulse extraction. The ion trap is produced by space charge of oscillating electrons in a drift tube region (radial confinement) and potential barriers on the boundary drift tubes (axial confinement). The electron cloud is confined by a solenoid magnetic field up to 5 T. This high field is also needed to exclude $^3$He nuclear depolarization in the ionizer.

For metastable atoms, the cross section of ionization at an electron energy of 10 keV is $\sigma_i^*(0 \to 1) \approx 7.3 \times 10^{-18}$ cm$^2$, that is, much larger than for atoms in the ground state ($\sigma_i(0 \to 1) \approx 2 \times 10^{-18}$ cm$^2$).
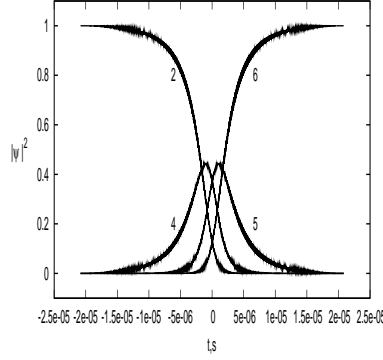
Figure 4: The probability for transition $2 \to 6$
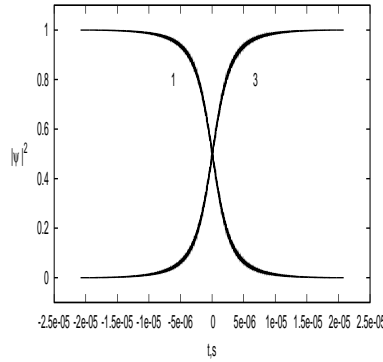


Figure 5: The probability for transition $1 \to 3$

The electron beam density for the ionization to $^3\mathrm{He}^+$ of metastable atoms with a velocity of $1.2 \times 10^5$ cm/s at the length of the ionizer 100 cm is 30 A/cm$^2$. The cross section $\sigma_i(1 \to 2)$ is $\approx 4.3 \times 10^{-19}$ cm$^2$. Then, at the electron density 30 A/cm$^2$ the confinement time for ionization to helions will be 15 ms. With the electron beam diameter of 5 mm, the effective electron current is 5 A.

The given mode has a number of advantages:

1. It is possible to inject $^3\mathrm{He}$ into the trap at the elevated pressure, which will lead to an increase in the ion charge in the trap.

2. Earlier, pulsed extraction of ions from the trap was carried out for 7 $\mu$s with a current of 1 mA, which corresponded to $4 \times 10^{10}$ charges [6]. With helium, it is really possible to get the 2–3 times higher intensity.

The design parameters of the ionizer are as follows:

• electron energy 10 keV,
• effective current $\approx 5$ A,
• ion trap length 1 m,
• helion intensity $\approx 2 \times 10^{11}$ ions/pulse.

The experiments [7] with the ionizer of the polarized deuteron source POLARIS (Fig. 6) show the feasibility of storing up to $4 \times 10^{11}$ charges in the ion trap.

The main elements of the future ionizer are a 5 T superconducting magnet, electronic optical system, 10 keV modulator, 8 $\mu$s system of fast extraction, and remote control system.

At the exit of the ionizer, it is necessary to install a deflecting magnet for separating

$^3$He$^{++}$ and $^3$He$^+$ ions. For helions, the $G$-factor is $-4.183963$; thus, to get transversal spin polarization, we need to deflect the beam by $21.5°$. Then, a special solenoid should rotate spin to the vertical direction, up or down.
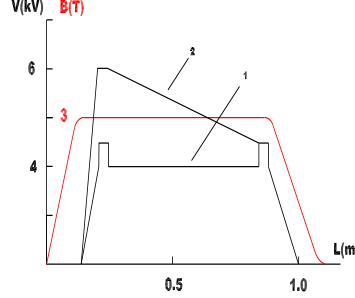


Figure 6: The distributions of magnetic field and voltage on the drift tubes at accumulation (1) and extraction(2) of the helions.

# 4   Depolarization effects

The time between metastability exchange collisions is $\tau = 1/\sigma vN$, where $\sigma$ is the cross section for the metastability exchange, $v$ is the velocity of metastables, and $N$ is the density of ground state atoms.
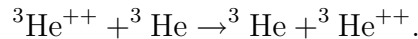
With $v = 1.2 \times 10^5$ cm/s and $\sigma = 4 \times 10^{-16}$ cm$^2$ [8], the condition for $\tau \gg T_{acc}$, where $T_{acc}$ is the time of accumulation, is

$$\sigma vN \ll T_{acc}^{-1} \ \ \text{or} \ \ N \ll 2 \times 10^{10} T_{acc}^{-1},$$

or $p \ll 6 \times 10^{-7}/T_{acc}$ Torr.

For $T_{acc} = 14$ ms, the required value is $p \ll 4 \times 10^{-5}$ Torr.

A dangerous process is the symmetric resonant charge transfer

$$^3\text{He}^{++} +^3 \text{He} \rightarrow^3 \text{He} +^3 \text{He}^{++}.$$

The cross section of this process is estimated to be $\simeq 7 \times 10^{-16}$ cm$^2$ [9], even larger than the cross section for metastability exchange.

Then, it is demanded that the background pressure of $^3$He be $p \ll 10^{-5}$ Torr.

Let a metastable flux be $6 \times 10^{15}$ atoms/s sterad. If we assume that the flux of atoms in the ground state is $\simeq 10^2$ times higher than the metastable flux, the pressure of the ground state atoms in the ionizer at the distance of 120 cm from the nozzle is $\simeq 10^{-8}$ Torr, which is acceptable.

When an atom or ion has an electron spin, the nuclear depolarization can be influenced by hyperfine interaction. Under an external field $B$, the primary nuclear polarization of the $^3$He atom is reduced in the intermediate $^3$He$^+$ ion by a factor $\alpha$:

$$\alpha = 1 - \frac{1}{2(1+y^2)},$$

where $y = B/B_c$, with $B_c = 0.3087$ T for $^3$He$^+$ ions. For $B = 1$ T, $\alpha = 0.956$.

The experience of the SATURNE group [10] shows that depolarization processes seem to be unimportant. They ionized $^6$Li$^+$ polarized ions to bare nuclei $^6$Li$^{3+}$ in the EBIS at the field of 5 T without depolarization during accumulation for 3 ms and extraction.

The degree of polarization in the course of acceleration can change when the spin frequency becomes equal to the integer combination of the frequencies of betatron and synchrotron motion in the region of the spin resonance, $\nu = \gamma G = \nu_k$,

$$\nu_k = k + k_z\,\nu_z + k_x\,\nu_x + k_\gamma\,\nu_\gamma\,,$$

where $\nu_x$ and $\nu_z$ are betatron frequencies, $\nu_\gamma$ is frequency of synchrotron motion.

Table 1[11] shows the number of linear resonances for different particle beams in the Nuclotron ($k$ and $m$ - integer, $p = 8$ - number of superperiods).

| Resonance type | Resonance condition | Number of resonances | | | |
|---|---|---|---|---|---|
| | | $^1H$ | $^2H$ | $^3H$ | $^3He$ |
| Intrinsic resonances | $\nu = k\,p \pm \nu_z$ | 6 | — | 8 | 9 |
| Integer resonances | $\nu = k$ | 25 | 1 | 32 | 37 |
| Non-superperiodical resonances | $\nu = k \pm \nu_z\,(k \neq m\,p)$ | 44 | 2 | 55 | 64 |
| Coupling resonances | $\nu = k \pm \nu_x$ | 49 | 2 | 63 | 73 |

Table 1: Linear resonances in the Nuclotron ring.

# 5    Conclusion

A possibility of developing a polarized helion source for JINR Accelerator Complex was discussed.

It seems possible to provide a polarized beam with polarization larger than 80% and helion intensity $\approx 2 \times 10^{11}$ ions/pulse of 8 $\mu$s.

The depolarizing effects in the polarized ion source are expected to be low.

For acceleration at the NUCLOTRON-M, it is necessary to provide conditions for low depolarization.

Installation of the polarized helion source at the JINR Accelerator Complex would allow the program of spin physics experiments to be extended.

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